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STEPPER MOTOR

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1.0 INTRODUCTION

The purpose of this document is to describe the more commonly used permanent magnet stepper motors for spaceflight. It will discuss the mechanical and electrical aspects of the devices, their torque behavior, those parameters which need to be controlled and measured and test methods to be employed. It will also discuss torque margins, compare these to the existing margin requirements and determine the applicability of these requirements. Finally it will attempt to generate a set of requirements which will be used in any stepper motor procurement and will fully characterize the stepper motor behavior in a consistent and repeatable fashion.

2.0 MOTOR CONFIGURATIONS

This section will discuss the more commonly used motor configurations for spaceflight and will show how these configurations are commutated. It will start with two phase design which is subdivided in single phase drive, center tapped drive and dual phase drive. It will continue with three phase design which is subdivided in either Y or DELTA configuration.

2.1 Two Phase

2.1.1 Single Phase Drive

Figure 1 shows the simplest two phase stepper motor configuration. The motor consists of a permanent magnet rotor and a stator containing two independent windings which are separated 90 electrical degrees. Depending on the number of poles or the magnetic structure of the motor, step size can vary from 90 mechanical degrees down. As long as 360° divided by four (4) times the desired step size is an integer any step size is theoretically possible and only limited by physical constraints. However, each mechanical step is equivalent to 90 electrical degrees.

Figure 1 also shows the commutation sequence. Powering the windings in the sequence shown will move the rotor in one direction. Reversing the sequence will cause the rotor to move in the reverse direction. The two phase motor has a four state sequence which repeats for continuous rotation. The motor as shown requires a driver which allows current to flow both ways. For that reason this configuration is also called a bipolar drive.

2.1.2 Center Tapped Drive

Figure 2 shows the center tapped version of the two phase stepper motor. Also included is the commutation sequence used with this configuration. This form of the motor was developed to simplify the drive system required. Normally each phase is bifilar wound and the windings are connected to provide the proper polarity.

Since the current in each coil only flows in one direction, this configuration is also called the unipolar drive. The performance of the two motor versions is identical and selection should be based on the implementation of the electronics drive system.

2.1.3 Dual Phase Drive

In the two phase steppers described, each phase of the motor was driven individually, one at a time, and sequenced in accordance with the associated logic table. This drive method generates a given torque and assures that the rotor will be in a stable magnetic detent position after power is removed from the motor. More about that later in the document.

With the dual phase drive both phases are powered simultaneously. The sequence of commutation is shown in Tables A and B of Figure 3 for the single and center tapped phase respectively.

The advantaged of driving both phases simultaneously is that peak torque is increased by a factor of $\sqrt{2}$ or 1.4. The disadvantage is that the rotor will be at an unstable magnetic detent after power is removed and will move either clockwise or counterclock-wise by half a step.

2.2 Three Phase

2.2.1 Y Connected

The Y connected three phase stepper is another popular version used for space flight use.

Figure 4 shows the Y connection and the commutation sequence used to step the motor. Here each commutation interval represents 60 electrical degrees. The six (6) intervals combine to provide for the 360 electrical degrees required and the sequence repeats for continuous rotation. Powering the windings in the ascending sequence shown will move the rotor in one direction. The commutation sequence also indicates that all three windings are used in each interval which implies efficient copper (wire) use. Also in this case, depending on the number of poles or the magnetic structure of the motor and the commutation sequence shown, step size can vary from 60 mechanical degrees down. As long as 360° divided by six (6) times the step size is an integer any step size is feasible and only limited by physical constraints. However, each mechanical step is equivalent to 60 electrical degrees.

2.2.2 Delta Connected

Figure 5 shows the delta connected 3 phase motor along with its commutation sequence. This sequence shows that in any of the six (6) intervals one of the three (3) terminals is not connected and left floating. But as with the Y configuration all available copper is still used. It will become clear a bit farther in this document that there may be some advantages to the delta versus the Y as far as the electronics goes. Otherwise the performance of the delta is the same as the Y. Some thought should be given to procure 3 phase motors with each phase brought out separately and not have the windings connected internally. This will allow for selection of delta versus Y at the electronic designer's discretion.

3.0 MOTOR PARAMETERS

This section will discuss the mechanical, electrical, and torque behavior and requirements that should be part of any specification for the procurement of stepper motors. Since stepper motors are generally driven open loop it is important to inform the motor manufacturer about the electronic approach being pursued driving the motor and that motor parameters should be evaluated with this information in mind.

3.1 Mechanical

3.1.1 Dimensions

Any specification must include the outline dimensions and tolerances of the motor package. In addition, it must be specific about the output shaft. Is it a plain shaft, a pinion, a shaft with a flat, how long, if a pinion, what gear pitch, how many teeth, what quality or finish, etc.? The mounting method should be specified in detail including the area where the wires exit the frame as well as the length of wires. However, not only are the external dimensions important, the internal dimensions and its tolerances can have a profound effect on the stepper motor performance. Although this is of primary concern to the manufacturer, step accuracy and cyclic bias errors may be introduced if the squareness of the stack ends relative to the stator bore, the tilt of the rotor with respect to the stator bore, and the rotor eccentricity are not controlled. These parameters become more and more critical the smaller the device and the smaller the step size.

3.1.2 Materials

The materials used in the construction of the motor should also be scrutinized. As is normal on any flight program a list of materials must be submitted for approval.

Magnet and lead wire should be selected from the Preferred Parts List (PPL) and wire insulation with respect to outgassing, radiation and temperature requirements. Potting compounds and lubricants should be selected for their outgassing properties in hard vacuum and must be cured and processed in accordance with established procedures. Surface treatment and/or chemical finishes and hardness of metals should be acceptable and samarium cobalt shall be used for the permanent magnet material.

3.1.3 Step Size/Accuracy/Repeatability/Rate

The step size along with its accuracy and repeatability is ultimately the parameter of greatest interest. The step size and accuracy are really determined by the resolution requirements of the task at hand. The step sizes possible with steppers was stated earlier and the accuracy of the steps depends on dimensions and tolerances of the stator and rotor. An accuracy of ±10% of the desired step size is what can be reasonably expected.

The repeatability is much more difficult to control. If only the motor is considered, the repeatability is influenced by the rotor inertia, the friction, the manner in which the motor is driven, and if the drive is uni- or bi-directional. This means, must repeatability be met regardless from which direction (CW or CCW) the desired position is approached. Repeatability is far more difficult to control and maintain in open loop systems which are used with stepper motors in the overwhelming number of cases. If the manufacturer is required to meet repeatability taking more than just the motor into account, a number of other quantities must be specified. The inertia of the load must be given, the gear reducer characteristics if used, external friction and its variation over the anticipated environment and life, operating modes, and the drive to be used.

In addition to step size, accuracy, and repeatability, it is essential that the maximum rate (slew rate) and normal operating rates along with their settling times be specified. All these quantities are required so the motor designer can take these parameters into account when determining the margins and size requirements of the motor.

3.1.4 Minimum Gap

The gap between the rotor and the stator is another quantity which requires attention. It is not at all uncommon to have gaps of .002 in. in motors which provide small step sizes. This is specifically the case with the so called "hybrid steppers" which refers to the internal magnetic configuration of the motor.

These small dimensions (.002 in.) makes the assembly sensitive to debris and requires care and vigilance to assure that particles do not enter the airgap and jam the rotor/stator. Further, operating temperature and gradients need to be assessed to assure that differences in temperature coefficients do not cause rotor to stator interferences.

3.1.5 Bearings

The quality of the bearings to be used shall be ABEC7 minimum. In most cases both the balls and races must be fabricated from CEVM440C CRES with a race finish of 2 micro inches rms and a ball grade of 5 or better. Only in special cases and with the prior approval of the customer may steels, such as 52100, be used. Before its use, handling procedures, which incorporate some form of rust prevention, should be in place. Whenever possible oil and grease lubricants are preferred over the dry kind. Even the worst wet lubricant is better than the best dry lubricant and dry lubricant should only be used when absolutely necessary and then only for limited life. There are a variety of oils used for spaceflight. The most popular being Pennzane 2000x, Braycote 815Z, and Krytox 143AC; popular greases are Nye Rheolube 2000, Braycote 601, and Krytox 240AC. Which one to use depends on the environmental conditions which will be encountered. At this time the dry lube of choice is molybdenum disulfide (MOS_2), preferably applied using a sputter coating technique.

The material for the bearing retainers should be either linen reinforced phenolic, grade LLB or porous polyimide. A machined full retainer is preferred but, if used, care must be taken in the bearing design since a bearing with full retainer can only handle loads in one direction. A bearing configuration using 2 bearings with a hard preload must be incorporated. Spring preload should not be used with these bearings. The alternative is to use deep groove bearings and a crown retainer. The fear here is that debris may be generated when installing the retainer. All retainers should be vacuum impregnated at room temperature and submerged in oil for a minimum of eight (8) days. Oil retention should be 3% by weight minimum.

The retainer for bearings with MoS_2 should be made from duroid, a material made from teflon, MoS_2 and glass fibers. Care should be taken operating MoS_2 lubricated bearings. The sensitivity of MoS_2 to moisture require that these bearings are operated only in vacuum or an environment well purged with dry nitrogen.

3.1.6 Preload

Preload of the bearings should be carefully selected. Often preload is selected to survive the launch environment without giving much attention to operation and life required throughout the mission. In general, during operation the preload only need to be sufficient to take up clearances but this is normally inadequate to take care of launch conditions. This situation can be remedied by providing either a preload sufficient to handle the launch conditions and live with this load for the life of the mission, a caging device which will take the launch load and upon release allows for a nominal preload required during operation, or a nominal preload required during operation and a stop. Since the preload is less than the preload required during launch, which will prevent unloading of the bearings, the load will move but the stop, which is placed to allow only small motions, will prevent large load excursions and thus limit the total amount of energy which can build up to values well below the value which can do damage.

It should be kept in mind that in any case the Hertzian stresses must be kept in bounds. For instance, stresses in 440C bearings should never exceed 350 KSi max/mean and if long life is required stresses should not exceed 150 KSI.

The preload also determines the bearing break away and coulomb friction which can introduce significant positional error in stepper motors which drive the load directly.

3.1.7 Load

It is important to specify the load and its characteristics when procuring a stepper motor. Since stepper motors are in the majority of cases driven in an open loop mode, its performance is governed by the inertia and friction in the system. In general, driving large inertias directly (inertias greater than twice the rotor inertia) should be avoided. Driving large inertias cause oscillations resulting in over or under shoot which reveals itself in missed or greater than anticipated steps. This may be more pronounced at certain drive frequencies and is due to the stepper torque characteristics around the stepper null position. The torque around null behaves as a spring which with the load inertia forms a spring/mass system with its characteristic resonance phenomena. The spring has two values, one with the motor powered and one with the motor unpowered in which case only the detent torque is effective. Also little damping is present. The drive electronics can improve the performance using feedback but this would add complexity to the drive. A gear drive would effectively reduce the load inertia by the square of the gear ratio but the gear drive friction, efficiency, and its contribution to the motor's inertia must be assessed and specified to assure sufficient drive margin. However, the real performance can only be properly predicted by a detailed, high fidelity dynamic analysis which must include the electronics and power supply.

3.1.8 Environment

The effect of the environment must be considered when selecting a motor. The vibration and shock environment determine the size of the bearings which can handle the load. It will have an effect on the selection of the preload, either fixed or spring, and location and size of the stops which may be incorporated to limit the load displacement and thus the total energy which can be gained by the load and must be dissipated.

The thermal operating range and associated gradients must also be considered. Fixed preloads may be affected due to temperature variations, especially gradients, and the small rotor/stator gap, often present in small angle stepper motors, may close up. Further, coulomb and breakaway friction may increase as a result of preload changes and viscous friction will be affected if wet lubricants are used. Selecting a lubricant with a low viscosity index will minimize this effect.

In addition, the number of operating cycles and the range of motion anticipated during the life of the device and the total time in orbit must be considered in selection of the techniques applicable for these requirements.

3.2 ELECTRICAL

3.2.1 Configuration

The various motor configurations discussed in Section 2 require electronics which are properly sequenced to provide the desired motion.

Figure 6 and 7 show two (2) methods to drive a two phase motor single phase.

The schematic depicted in Figure 6 uses both a positive and negative power supply. Phase AB is connected via semi-conductor switches either to the positive supply when Y is positive or to the negative supply when Z is positive. When Y is positive, conventional current flows from the positive supply through the switch entering the motor phase at A leaving the phase at B and completing the circuit through the ground return. When Z is positive the current flows in the opposite direction entering the phase at B leaving at A through the switch and completing the circuit through the negative supply. The waveform shown and identified as Y, Z, Y' and Z' drive the switches in the desired sequence to provide rotation. Y and Z drive phase AB while Y' and Z' drive phase CD in a corresponding fashion. The intervals identified as 1, 2, 3, and 4 show the four conditions required to move through 360 electrical degrees. These intervals as well as the AB and CD phase designation are the direct equivalent of those shown in the table associated with Figure 1.

Figure 7 shows the schematic of a single phase drive for a two phase motor using one supply. To force current to flow through the coil from A to B, switches W an Z are turned on, to reverse the current switches X and Y are turned on. The other phase is driven in an identical fashion where corresponding switches are activated with signals W' and Z' and for reversing the current with signals X' and Y'. Again intervals 1, 2, 3, and 4 show the four conditions required to move through 360 electrical degrees.

Figure 8 shows the drive associated with motors having a center tap. The drive sequence is identical to that shown for Figure 6. It is obvious that this configuration simplifies the drive electronic; it requires only one supply as in Figure 7 but only needs two switches per phase as in Figure 6. Electronically it possesses the best of both "worlds".

However, to obtain the same performance as the motors shown in Figure 6 and 7, twice the number of turns must be wound onto the motor stator. This may increase the size and weight of the motor.

Any of the circuits shown can be driven in the dual phase mode. The waveforms driving the various switches are shown in Figure 9. The torque obtained, driving the motor in this configuration, is 1.4 times greater than driving it single phase. However, the null position of the stepper is at an unstable detent. (More about that later.) Care must also be taken when designing the drive circuitry. As can be seen, this sequence requires that the top and bottom switches are being activated and deactivated simultaneously. In other words the top switch is turned off at the same time the bottom switch is turned on and visa versa. Unless some delaying sequence, synchronized with the pulse rate and of sufficient duration to accommodate the motor's electrical time constant, is incorporated in activation of the switches, large supply transients, which may be catastrophic, may result since both top and bottom switches may conduct at the same time and actually short out the supply.

This same precaution is valid for the circuit and switch activating sequence shown in Figure 10. This is the circuit most commonly used to drive the Y connected three phase stepper motor version.

In the three phase configuration there are six switching intervals per 360 electrical degrees of the motor. These intervals are shown below the waveforms and marked 1 through 6, each interval equivalent to 60 electrical degrees. This sequence correspond to the switching table shown in Figure 4.

Figure 11 is the same circuit but driving the three phases in a delta configuration. The switching sequence is also shown and the switching intervals correspond to the intervals shown in Figure 5. There is an important difference between these and the previous waveforms. In the Y configuration it shows that the U switch is turned off at the same time that the X switch is turned on. This opens the possibility that during the transition, a large transient may be generated because both switches may be conducting at the same time causing a power supply short. Actually, each switch is on and off for an interval of 180 electrical degrees. The sequence for the delta configuration does not have this drawback as shown in Figure 11. Each switch is on for 120 electrical degrees and off for 240 electrical degrees. It is also apparent that the on period of the top and bottom switches are separated by 60 electrical degrees. This eliminates the possibility of both top and bottom switches conducting simultaneously and generating a large transient.

3.2.2 Motor Resistance/Inductance

The motor resistance and inductance are important parameters which must be controlled or specified when procuring stepper motors. The motor resistance will determine the peak current, and thus the peak torque, which will be drawn at stall assuming a constant voltage drive. Further, it will determine the maximum power (I^2R) that needs to be dissipated and the associated temperature rise in the windings, which in turn depends on the thermal conductivity from motor winding to the thermal sink and its temperature.

The inductance determines the time it takes for the motor current to reach its peak value and also the time needed to discharge the energy stored in the inductor. Unless the circuitry is designed to handle the discharge, large and unacceptable transients may occur. In specifying motor characteristics it is common practice to list the ratio of motor resistance versus motor inductance as the electrical time constant. Ultimately, the time constant is the limiting factor determining the highest motor speed since it controls how fast the current can reach its final value. This is based on driving the motor through a constant voltage source; if a constant current drive is used the effective electrical time constant is reduced for small signals, if however, large currents are demanded, the drive will hit the voltage rail and saturation effects will rule the circuit's behavior.

3.2.3 Drive Method

To obtain the required performance of a stepper motor, the method of driving the device is of prime importance. The first requirement to be specified should be the speed of operation which will translate into the pulse repetition rate required to drive the circuitry. Stepper motor/load combinations normally have a maximum lock-in rate which is that pulse repetition rate at which the motor/load can be driven starting from a dead stop without loosing synchronization. Within reason, rates higher than the lock-in rate can be achieved by ramping the pulse rate from the lock-in to a higher rate. When approaching its final position the pulse rate may have to be ramped down before settling into that position.

After the pulse repetition rate has been established, the pulse width should be determined. The pulse width along with the pulse rate govern the power in the motor and thus the torque output and torque margins. When possible the last pulse should be left on to aid in meeting the step settling requirements before relying on the magnetic detent forces to hold position.

Every time the drive pulse switched on or off the motor inductance is charged or discharged. Unless properly handled, large transients are generated when motor current is turned off instantaneously, which is normally the case with drive pulses having short rise and fall times. The more conventional way in handling these transients is first to parallel the transistor or Field Effect Transistor (FET) switch with a diode. Figure 12 shows the implementation and is a modified version of Figure 7. Assume that the current I flows as shown since switch W and Z are conducting. As soon as W and Z are turned off and since the current through an inductor cannot change instantaneously, terminal B is clamped to ground through diode 4 and the potential at terminal A will rise until diode 1 conducts. What happens next depends on the supply characteristics. If the supply impedance can both supply and absorb current, the energy stored in the inductor will dissipate in the supply impedance and the supply voltage will momentarily rise to a level depending on the impedance value. However, often supplies cannot absorb currents or system requirements prohibit the introduction of large transients on the power distribution network, so transients must be handled locally at the motor drive circuit level. A capacitor across the supply terminals would be an approach but, in general, stored energy is so high that the required capacitor value and size are too large to make that approach practical. Another approach is to connect a zener diode across the supply terminals, its breakdown voltage a couple of volts above the maximum anticipated supply voltage. When the transient reaches the breakdown voltage, the zener conducts thus providing a path for the discharge current. A more elegant solution is possible by simply modifying the timing of the drive signals for the switches. The required waveforms are shown in Figure 12. Assume current I flows as shown. Instead of turning both switches W and Z off at the same time only switch W is turned off disconnecting the motor from the supply. Switch Z is kept on and the discharge current now flows from terminal B through switch Z and diode 3 back to terminal A providing the necessary path for discharge. The resulting current waveform is also shown in Figure 12.

It should be realized from this that to generate appropriate stepper motor requirements, parameters, and specifications, it is essential that an analysis/simulation of sufficient fidelity, which should not only address the motor but also include the electronics and the power supply, must be performed.

3.2.4 Drive Voltage/Power

Along with other parameters such as load, stepping rate, step size, etc., the motor designer must know the available drive voltage and power. This allows for proper sizing of the wire gage for the motor windings; normally not smaller than 40 AWG, , the number of turns, the stack height and diameter, and selection of the materials to be used. Within a known size and volume the designer must manipulate and trade off these parameters to meet the requirements. Since part of the power is dissipated in heat, the design should allow for a proper thermal path from the windings to the external housing which must be connected to the external environment to keep the internal rise within bounds.

3.3 Torque

To discuss the torque profile of both 2 phase and 3 phase permanent magnet steppers it is important to adhere to a consistent convention in expressing torque, current, back EMF and rotor position. For the sake of this discussion, waveforms shown are the waveforms of the back EMF measured from the unmarked end of the winding to the dot marked side of the winding assuming clockwise rotation and are plotted against the angle between the rotor and the stator. Further, the waveforms are also the torque profiles generated by the windings with current entering the dot marked side of the winding and where positive torque will generate clockwise rotation.

3.3.1 Torque Constant

The torque generated by a given motor depends on the current I through the armature, the angular position θ of the rotor with respect to the stator, and the motor torque constant $K\tau$, a parameter unique for each type of motor. Since the torque is sinusoidal with respect to position, the expression can be written as:

$$T = K\tau I \sin \theta$$

This is the torque generated by one phase of the motor. $K\tau$ is normally expressed in in.oz/amp or Nm/amp. $K\tau$ can be determined by inducing a known current in the winding and measuring the maximum torque. At maximum torque $\theta = 90°$ and $\sin \theta = 1$, thus;

$$T_{max} = K\tau I \quad \text{or} \quad K\tau = \frac{T_{max}}{I}$$

3.3.2 Powered Torque

Figure 13 shows the torque profiles generated by each phase of a two phase motor. Curve K shows the torque produced by winding A-B of Figure 1 with current entering A. Curve L is the same for winding C-D with current entering C. The ordinate is torque and the abscissa is angle between rotor and stator. N is the number of pole pairs. The amplitude of the torque depends on the motor current. Positive torque moves the rotor clockwise or from left to right in Figure 13 and negative torque moves the rotor in the opposite direction. To move one step let us assume we are at $\theta = 90/N$. Applying power across A-B as shown in the commutation table of Figure 1 will generate positive torque moving the rotor from $\theta = 90/N$ to $\theta = 180/N$ where torque is zero. Next power is applied across C-D generating a torque moving the rotor from $\theta = 180/N$ to $\theta = 270/N$. Now, according to the commutation table, power is applied again across A-B but current is now entering the B terminal. The current being negative but also the value of the sinewave now being negative, generates again a positive torque moving the rotor from $\theta = 270/N$ to $\theta = 360/N$. This process is repeated for phase C-D moving the rotor from $\theta = 360/N$ to $\theta = 450/N = 90/N$. Now the entire cycle can start over again. This same process is valid for Figure 2 except instead of reversing the current through the winding a separate winding is activated essentially having the same effect.

More torque can be generated by powering both phases simultaneously, shown in the commutation tables of Figure 3. By using the indicated sequences we actually are summing two waveforms as shown below:

1. $T = K\tau I\ (\sin\theta + \cos\theta) = 1.41\ K\tau I \sin(\theta + 45°)$

2. $T = K\tau I\ (-\sin\theta + \cos\theta) = 1.41\ K\tau I \sin(\theta - 45°)$

3. $T = K\tau I\ (-\sin\theta - \cos\theta) = 1.41\ K\tau I \sin(\theta - 135°)$

4. $T = K\tau I\ (\sin\theta - \cos\theta) = 1.41\ K\tau I \sin(\theta - 225°)$

The waveform M of Figure 13 is a graphic presentation of commutation sequence #2. It clearly shows the increased torque and here a step will go from the peak torque at $\theta = 135°/N$ to $\theta = 225°/N$ where torque will again be zero.

The torque profiles of the three phase motor, both Y and Delta wound are shown in Figure 14. Waveform A, B, and C are the torque profiles of each winding.

Following the previous stated convention and using the Y connected windings and the commutation table of Figure 4, we sum three waveforms and obtain the following torque intervals (Figure 4):

1. $T = K\tau I \sin \theta - \frac{1}{2} K\tau I \{\sin(\theta + 120°) + \sin(\theta - 120°)\}$
$= 1.5\ K\tau I \sin \theta$

2. $T = \frac{1}{2} K\tau I \{\sin \theta + \sin(\theta - 120°)\} - K\tau I \sin(\theta + 120°)$
$= 1.5\ K\tau I \sin(\theta - 60°)$

Abbreviating gives:

3. $T = 1.5\ K\tau I \sin(\theta - 120°)$

4. $T = 1.5\ K\tau I \sin(\theta - 180°)$

5. $T = 1.5\ K\tau I \sin(\theta - 240°)$

6. $T = 1.5\ K\tau I \sin(\theta - 300°)$

The dashed profiles partially show these six (6) waveforms which, in this, case provide CCW torque. Assuming we are at position $\theta = 360/N$ the first step CCW is interval 3 which moves the motor to $\theta = 300/N$. Next interval 2 moving the rotor from $\theta = 300/N$ to $\theta = 240/N$ and so on till after interval six when the whole sequence will be repeated.

The identical equations can be derived for the delta connected configuration and the stepping sequence is the same (Figure 5).

3.3.2 Detent Torque

All permanent magnet (PM) stepper motors have detent torque. It is the equivalent of cogging torque encountered in permanent magnet DC motors where motor design attempts to minimize the affect. In PM stepper motors the effect is emphasized. The torques generated by the detent will tend to hold the motor rotor in a fixed, stable position, in general, one of the desirable characteristics of a stepper, since it is commonly operated in an open loop fashion. Without the detent, position may vary under the influence of small disturbances. With the detent a restoring torque is present driving the rotor back to its original position. The detent torque is a direct result of the motor geometry and in a two phase stepper the frequency of the detent torque is 4 times that of the frequency of the electrically generated torque. Figure 13 shows the detent torque in relation to the electrically generated torques. Figure 15 shows the single phase driven waveforms separately along with the detent torque. The dashed waveforms show the combined torque profile and that is the torque produced by the motor for a certain current value. Taking step 1, which will move the position from $\theta = 90/N$ to $\theta = 180/N$, generates a torque slope at the null position as indicated by the dashed line when power is supplied. This torque slope is a spring ($T = K\theta$). This spring in combination with the load may generate a damped oscillation at null. After the power is removed only the detent torque remains. This torque reflects a different slope and thus a different frequency of oscillation when disturbed. It should also be noted that the powered torque and the detent torque slope have the same sign around null. This means that both torques will drive the load to the desired null position so if disturbed the restoring torque will tend to maintain the original position. This is called a stable null. Figure 16 shows the same curve but for the dual phase drive. It is indeed true that higher peak torques are available using this drive but due to the phase shift introduced in the electrically generated torque, the combined electrical and detent torque profile is rather different. The single step indicated starts at $\theta = 135/N$ and ends at $\theta = 225/N$. Here it shows that the torque slope of the powered torque and detent torque are of opposite sign. Actually, if power is removed and the rotor is not exactly at null, the detent torque will move the rotor either to $\theta = 180/N$ or $270/N$ depending on which direction the position deviated from $\theta = 225/N$. This is called the unstable detent null and is one of the undesirable characteristics of the dual phase drive. Another is that around the powered null position, the torque slope is rather flat and therefore position errors may be large.

Figure 17 shows the torque profiles along with the detent torque for a three phase stepper. In the three phase design, the frequency of the detent torque is a factor 6 larger than the frequency of the powered torque profile. The dashed line again shows the combined powered and detent torque. Step 1 would take the rotor from $\theta = 120/N$ to $\theta = 180/N$. Again it can be seen that there the slopes of the powered and detent torque are the same sign and position will be stable. Figure 18 shows the actual plots of the torques generated by a three phase Y wound stepper and good correlation with Figure 17 is apparent. The actually measured detent shows a slight skew but presenting the detent as a sinewave is still a good first order approximation. The detent torque magnitude and its allowed variation should be specified.

3.3.4 Powered/Detent Torque Phasing

Figure 13 through 17 show that positional accuracy of the stepper is affected by the phasing between the powered and detent torques. If the powered null torque and the detent null torque are not coincident, the rotor would either shift clockwise or counter-clockwise when power is removed. How much depends on the phase shift between the two. It is reasonable to specify that the error introduced by improper phasing of the powered and detent torque must not exceed ±10% of the motor step size. Greater accuracies may be achieved but this required that particular attention be paid to mechanical tolerancing, rotor to stator concentricity, rotor eccentricity, stator stack squareness and flux uniformity.

3.3.5 Frictional Torque

Now that we know what torques are generated by the motor it is time to discuss what torques need to be overcome. The first, and possibly the more difficult to specify and control, are the frictional forces. These consist of break away, coulomb and viscous friction. Friction always opposes motion, it behaves like a brake. Breakaway friction is the static friction which needs to be overcome to start motion, after motion starts coulomb friction, which is a constant drag independent of velocity, and viscous friction, which is velocity dependent, come into effect. The effect of viscous friction must be determined at the operating point of the stepper and all friction components must be evaluated under worst case conditions. It is unfortunate that friction may vary greatly over its operating environment and life and it is prudent to design steppers with a sufficient margin to assure successful operation. Further hysterisis and eddy current losses are present in magnetic circuits with varying fields. The losses also create torques which oppose motion and must be accounted for when determining minimum torque requirements for a motor. The motor manufacturer should provide data quantifying this losses.

3.3.6 Inertial Torque

The required performance of stepper and its load normally determine the inertial torque required. It is the torque which must accelerate and decelerate the load. Care should be taken when driving large inertial loads with steppers. In general, steppers do not like to drive large inertias. If inertias, several times larger than the rotor inertia, are to be driven, one should consider driving the inertia through a gear reduction. The reflected inertia is then reduced by the square of the gear ratio. Of course, also the reflected frictional torques must be taken into account. Fortunately inertial loads do not vary with life or environmental conditions. The motor only has to accommodate the inertia and its uncertainty present in the initial calculation of the inertia.

4.0 TORQUE MARGIN

A stepper should be selected with sufficient margin to assure that, at its operating point under worst case conditions, it will perform with the required accuracy and over its expected life. Stepper motors are used quite differently than the better understood commutated DC motor, which has a rather constant torque for a given current and which is normally used in a closed loop configuration. Steppers, on the other hand, are used in an open loop configuration and torque, for a given current, ranges from its peak value to zero, which is normally its desired rest position.

4.1 Static

If we assume that the speed at which the stepper motor performs its task is not important then the static torque margin can rather easily be gleamed from the graph shown in Figure 19 since the viscous friction, the $I\alpha$ term to accelerate the load, and the back EMF are all zero. Only breakaway and coulomb friction are the quantities the system has to cope with.

Figure 19 shows the torque profiles of a two phase motor. Coulomb friction is shown as a torque opposing CW motion. This torque will effectively subtract from the available torque and that is graphically shown by the line labeled "Projected Friction".

Moving from $\theta = 0$ to $\theta = 90/N$ by powering phase 1, the torque follow the profile shown, which is essentially a sinewave. The desired position is $\theta = 90/N$, however, at point A the available drive torque equals the coulomb friction torque and motion stops. Instead of ending up at $\theta = 90/N$, the final position is at B. A position error due to the friction has been introduced. Looking at it from the opposite way, if the maximum allowable system error is known, the maximum allowable coulomb friction for a given motor can be calculated or the motor can be seized for a given coulomb friction. Figure 19 also shows that if friction exceeds the level indicated at C, and where phase 1 and phase 2 profiles cross, all motion will stop. Although phase 1 may have moved the load, if the friction is sufficiently high so the load moves less than a angle $\theta = 45/N$, the torque available from phase 2 is insufficient to overcome friction. It should therefore be realized that the available and useful torque of a two phase stepper motor is only 0.707 times the peak torque.

The breakaway torque is normally higher than the running coulomb friction and must also be evaluated. However, in systems that drive the load directly, the allowable coulomb friction is dictated by the accuracy requirements and sufficient reserve torque will probably be available to overcome breakaway. Since friction is rather unreliable and varies with the environment and life, worst case conditions must be used to evaluate the systems performance and the torque ratio on friction should be at least a factor of 4.

The conditions for the three phase configuration are the same except that here the available and useful torque is 0.866 times the peak torque.

4.2 Dynamics

Although the static torque margins must be evaluated, a more realistic approach needs to include the dynamics of the system. This should not just address the stepper motor and its load but must include the motor drive as well, since that has a large influence on the systems behavior. Now, in addition to the breakaway and coulomb friction, the viscous drag, the $I\alpha$ torque, and the back EMF must be taken into account. Also the implementation of the drive electronics must be included in the evaluation. It is important to the system performance to know how the transients are handled, what the impedance of the power source is, the pulse rate, the pulse width, what damping is provided, saturation levels, nonlinearities, etc. and how to determine what margins are required.

The only realistic way to get a handle on that is to develop a high fidelity model and perform a parameter sensitivity analysis. Especially the parameters, mainly friction and preloads, that vary over the environmental range and life should be tested. It is difficult to physically test for these variations because the variations are difficult to introduce into actual hardware. The model can initially be used to generate a motor procurement specification but after hardware has been built the model should be verified and updated if necessary and then parameters should be varied to establish the systems performance envelope. Torque ratios of 4 or better should be maintained for those parameters that vary with the environment and over life.

4.3 Effect of Drive Methods

The method chosen to drive the stepper motor does have an effect on the torque margin. Since a stepper motor is a device that changes electrical energy into mechanical energy, the mechanical output is directly proportional to the electrical input. To make a torque margin evaluation it is important to know the following conditions; is power applied continually between steps, is the system pulsed, what is the pulse width and what is the pulse rate, and is the system voltage or current source driven? If the pulse width is small compared to the time it takes for the load to reach its final position, then the system relies on the inertially stored energy to carry the load against friction and possible rate damping generated from the back EMF to that position. If that is the case, position errors may be large if friction varies over environment and operating life as it surely will.

Further the motor electrical time constant has an effect on the current build up and decay which may limit the pulse width at high pulse rates. Of course, these effects must be evaluated at the operating point of the system.

4.4 Stepper Motor Margin/Existing Margin Specification Comparison

The appendix shows a copy of the existing torque margin specification. Review of specification shows that it is more applicable for deployable systems where speed or lack of it is of no great concern. Only when the stepper is essentially operating in a static mode does the specification provide guidance. Since each step of a stepper motor at its final position results in zero torque, torque margin at that point does not make sense. The final result of a step must be judged against the positional performance requirements. Is the friction so large that final position accuracy cannot be achieved? Are we getting there within the specified time? Does the system settle in time? These are the questions to be asked.

It is appropriate to run the tests to determine the quantities listed under "Required Tests: "Part a" of the margin specification and the quantities are applicable. In addition, the motor must be properly characterized. The torque constant K_τ should be measured, the torque profile at a known current as well as the detent torque profile must be plotted, and the back EMF determined.

"Part b" of the required tests determine the resistive torques. With steppers the resistive torques must include the breakaway and coulomb friction, the viscous friction, including dampers if employed, hysterisis and eddy current torques, the torque required to accelerate or decelerate the load, and the back EMF effects. These quantities along with the time in which the particular motion must be completed will provide a number for the resistive torque. This is probably a number generated from a model which has been verified using measurements derived from actual hardware.

The minimum required test verified torque ratios listed could be used provided they are measured at the systems operating point i.e., within the time and accuracy specified.

5.0 TEST METHODS

Various stepper motor parameters, listed below, must be measured and recorded so these quantities can be used in modeling and simulation of the system. Some measurements require special equipment which is not available in all laboratories. However, frequent users of motors may want to invest in the proper instrumentation to be independent and able to verify measurements made by the motor manufacturer who should supply this data as a matter of course.

5.1 Torque Constant

There is a direct relationship between the back EMF constant K_v and the torque constant K_τ. In the MKS system K_v in volts/rad/sec is numerically equal to K_τ in Newton meter/amp.

For a two phase motor K_τ is measured simply by driving the rotor at a constant, known speed, and measuring the peak voltage across the terminals of one phase with a scope. Knowing the speed in rad/sec. and the peak amplitude in volts gives:

$$Kv = \frac{\text{V (measured)}}{\text{rad/sec}} = K\tau \frac{\text{NEWTON METER}}{\text{AMP}}$$

For the three phase delta connected configuration the derivation is identical, for the three phase Y, without the center tape being available, two phase terminals must be connected together and the voltage measured between these terminals and the remaining one. Kv per winding is then:

$$Kv = \frac{2}{3} \times \frac{\text{V (measured)}}{\text{rad/sec}} = K\tau \frac{\text{NEWTON METER}}{\text{AMP}}$$

The 2/3 factor must be introduced because the derivation for torque in Section 3.3.2 shows $T = \frac{3}{2} K\tau I \sin \theta$.

5.2 Powered and Detent Torque and Phasing

To measure the detent and powered torque and their phase relationship special equipment is required. The test configuration is shown in Figure 20. The output shaft of the motor under test is connected first to a position encoder, then a torque transducer and finally to a geared motor or a magnetic particle brake. It is assumed that the encoder and transducer are calibrated and the X-Y plotter sensitivity is set to cover the range of anticipated torques and angular excursion. To measure detent torque the motor under test must be unpowered. Now operate the geared drive motor in both clockwise and counterclockwise direction and record the test motor torque on the X-Y plotter.

To measure powered torque, the motor under test should be powered with a known current from PS1 and the clockwise and counterclockwise rotation using the geared drive motor should be repeated and the torque recorded on the X-Y plotter. To be complete this measurement should be repeated to record the powered torque for each commutation interval. A graph such as shown in Figure 18 should be the result of these measurements. Now that both the detent and the powered torque are plotted on the same graph, the phase relationship between the detent and powered torque can be determined.

5.3 Power

Motor power under various loads and speeds can also be measured using the configuration shown in Figure 20. Instead of the geared drive motor we now introduce a magnetic particle brake, which is a device that produces a known braking torque for a given current. Varying the current varies the level of brake torque. If required a simulated load inertia can be introduced and mounted directly to the torque transducer shaft. The appropriate driver to drive the motor at its proper rate should be used instead of PS1. Now the motor can be operated and its behavior can be recorded on the X-Y plotter. If speeds are too high, use a X-Y memory scope with a camera to provide a permanent record. To observe the motor's sensitivity to friction and to establish torque margins the current in the magnetic particle brake can be varied from 0 to levels where the motor starts missing steps. Measuring both voltage and current will also allow for calculating power under various conditions.

5.4 Resistance and Inductance

Resistance and inductance of the motor should also be measured and recorded. A standard Ohm Meter and Inductance Bridge will be adequate to perform these measurements. These measurements should be made for all commutation intervals.

5.5 Preload

Figure 21 shows a bearing arrangement spring loaded in a face to face configuration. The spring preload can be measured in situ by supporting the housing and applying a force F, as indicated, and measuring the shaft deflection. Plotting the force versus deflection should provide a plot shown on the right of Figure 21. Applying the force at first will not cause any substantial deflecting until the force equals the spring force. At that point the bearing will slide inside the housing and the spring will be further compressed. Point A indicates the preload. From point A to point B the spring rate is measured and after point B the spring is fully compressed and no further deflection will occur. This measurement is only valid for bearings which are spring load. Measurements should be made for both increasing and decreasing loads. Fixed preloads cannot be measured in situ. External bearing preload measurements must be relied upon.

5.6 Environment

As a minimum the motor performance should be measured over the specified temperature range and if possible in vacuum. The most direct way is probably to mount the motor in the chamber with the output shaft penetrating the chamber wall. The load inertia, encoder, torque transducer and magnetic particle brake can then be mounted externally and the motor behavior along with its available margin can be evaluated over the full environmental temperature range. In addition to the equipment listed, the motor should have thermocouples installed so the temperature of the unit can be monitored throughout the test.

6.0 CONCLUSION

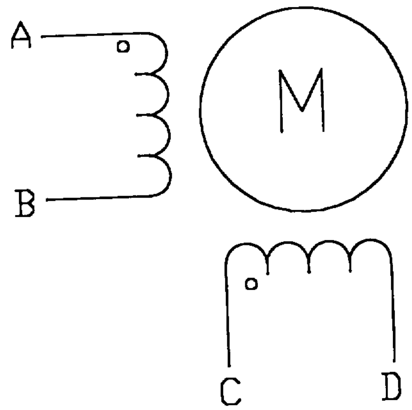
This document tried to describe the behavior of various types of permanent stepper motors and to highlight which performance parameters are important to obtain desired behavior. It showed that the present torque margin specification is not adequate to determine if sufficient torque margin is provided. The peculiar dynamic behavior and the operation around zero torque at its rest position along with the detent torque characteristics of a stepper does require closer attention. It is essential that a high fidelity model of the motor along with its drive electronics be generated. This model should be verified as soon as hardware is available and then the model can be pushed to determine the stepper motor system's envelope. Further it is essential that the appropriate test hardware to properly evaluate a stepper and the software to model and simulate the stepper behavior should be readily available to users of stepper motors.

In general in three phase Y connected motors the phases are connected internally and secured inside the encapsulated windings. It may be desirable to have all windings brought out separately so the user can choose if it is better to use a Y or Delta connected motor.

A list of parameters which must be included in any procurement specification is given below:

1. Overall Dimensions/Tolerance
2. Mechanical Interface/Tolerance
3. Load
4. Step Size/Accuracy/Repeatability
5. Preload
6. Torque Constant/Tolerance/Variation
7. Detent Torque/Tolerance/Variation
8. Powered Torque/Detent Torque Phasing
9. Resistance and Inductance
10. Operating Speed
11. Drive Method
12. Power
13. Lubrication
14. Step Settling Time
15. Environment
16. Materials
17. Coulomb Friction
18. Viscous Friction
19. Hystensis Losses
20. Eddy Current Losses

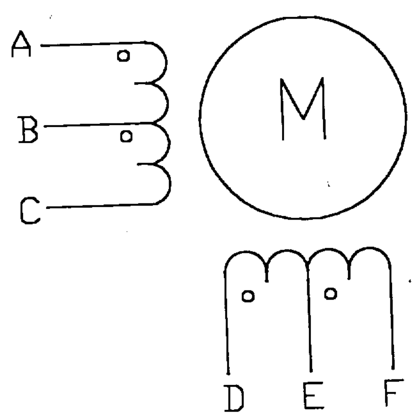
Plots of detent torque and powered torque versus position should be supplied by the manufacturer for each motor. This information will visually show the torque behavior of the motor and will allow for verification of the torque constant as well as phasing of the powered and detent torques. It will also show the variation of these torques over their range of operation.



	A	B	C	D
1	+	−	O	O
2	O	O	+	−
3	−	+	O	O
4	O	O	−	+

FIG. 1

Single Phase Configuration



	A	B	C	D	E	F
1	+	O	−	O	O	−
2	O	O	−	+	O	−
3	O	+	−	O	O	−
4	O	O	−	O	+	−

FIG. 2

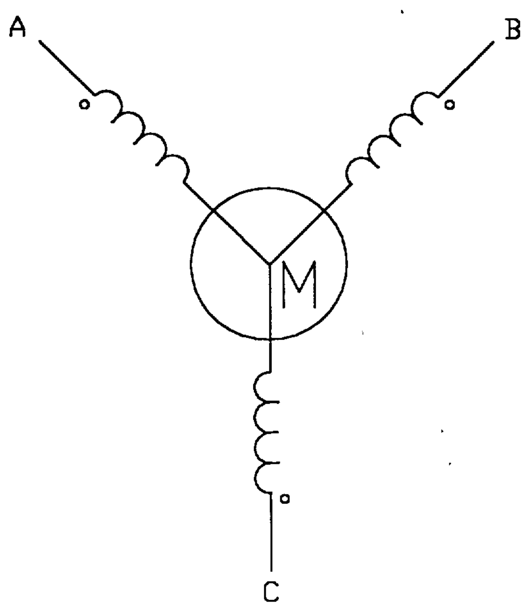
Center Tapped Configuration

	A	B	C	D
1	+	−	+	−
2	−	+	+	−
3	−	+	−	+
4	+	−	−	+

	A	B	C	D	E	F
1	+	o	−	+	o	−
2	o	+	−	+	o	−
3	o	+	−	o	+	−
4	+	o	−	o	+	−

FIG. 3

Dual Phase Configuration



	A	B	C
1	+	−	−
2	+	+	−
3	−	+	−
4	−	+	+
5	−	−	+
6	+	−	+

FIG. 4

Three Phase Y Configuration

	A	B	C
1	+	−	O
2	+	O	−
3	O	+	−
4	−	+	O
5	−	O	+
6	O	−	+

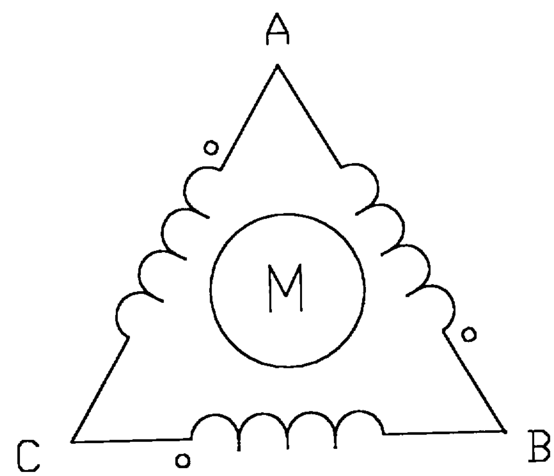


FIG. 5

Three Phase Delta Configuration

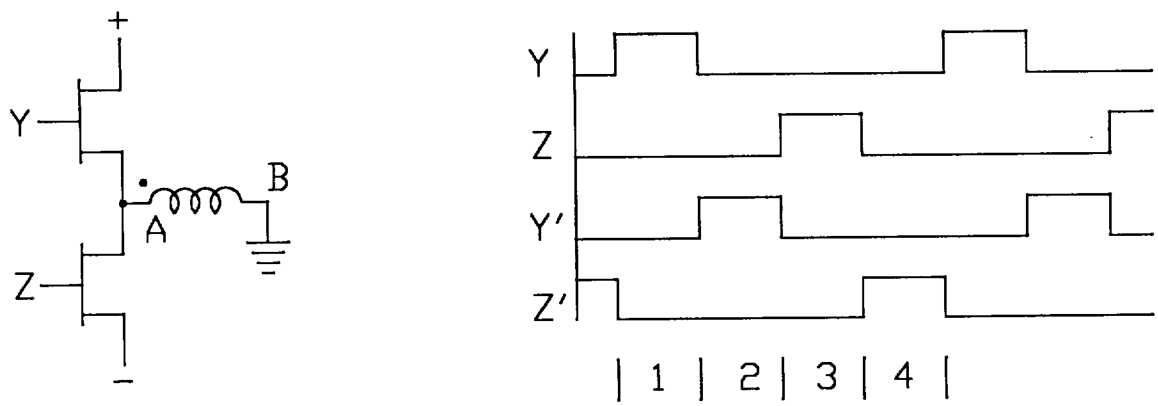


FIG. 6
Bipolar Drive

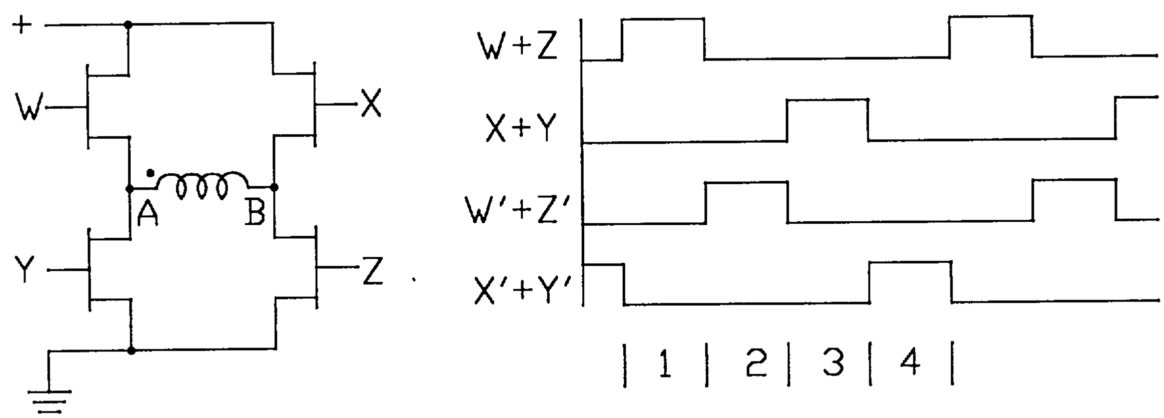


FIG. 7
Bipolar Bridge

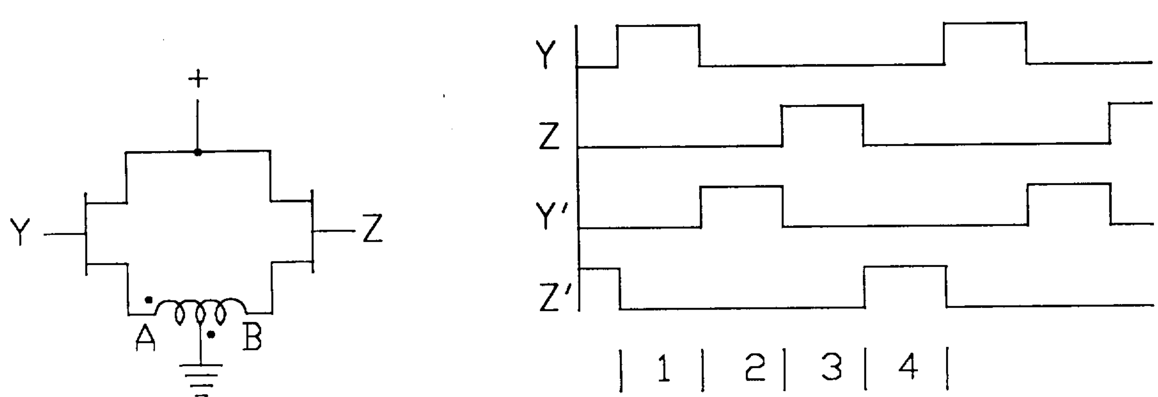


FIG. 8
Unipolar Drive

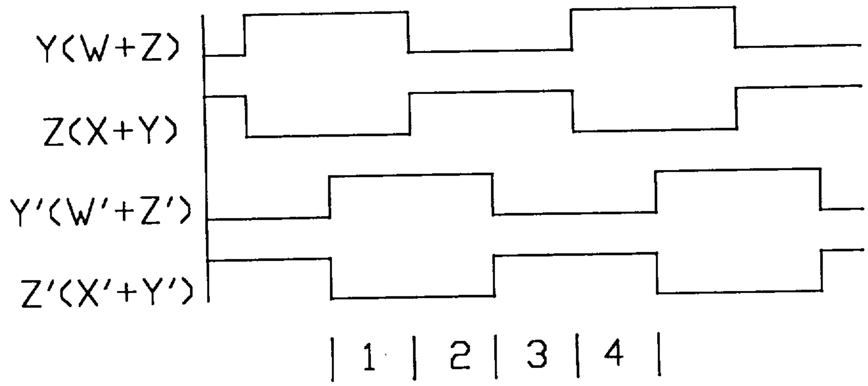


FIG. 9
Dual Phase Drive

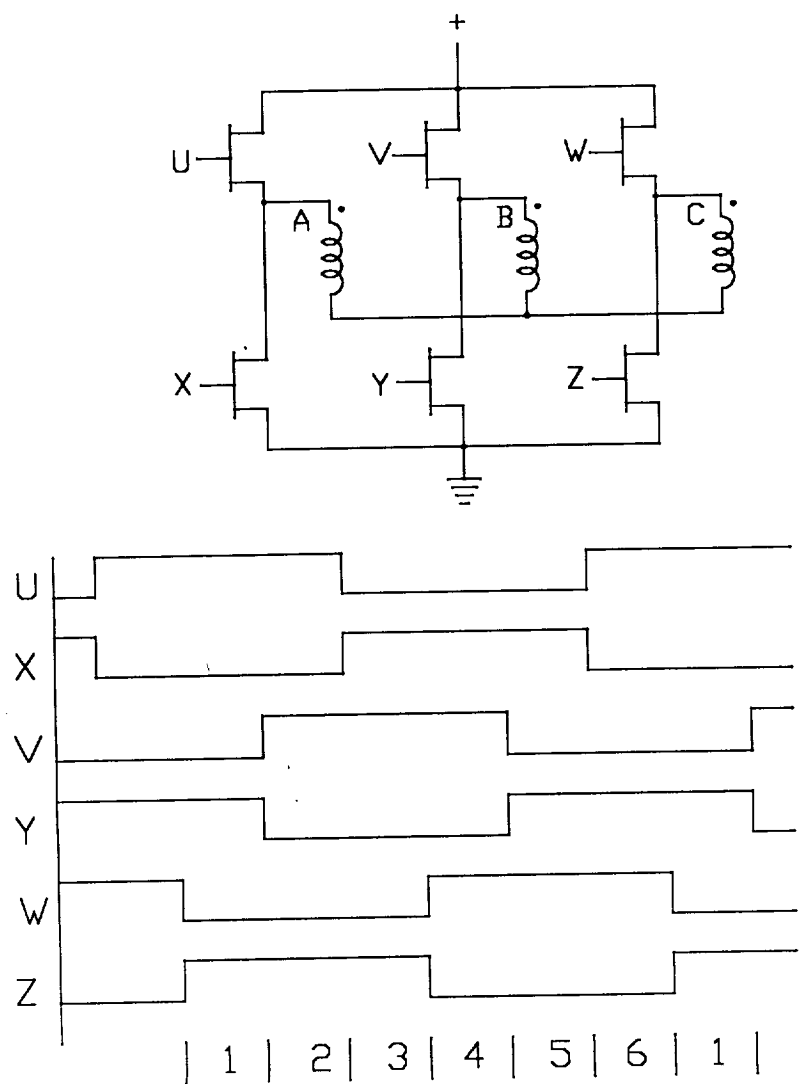


FIG. 10
Three Phase Y Drive

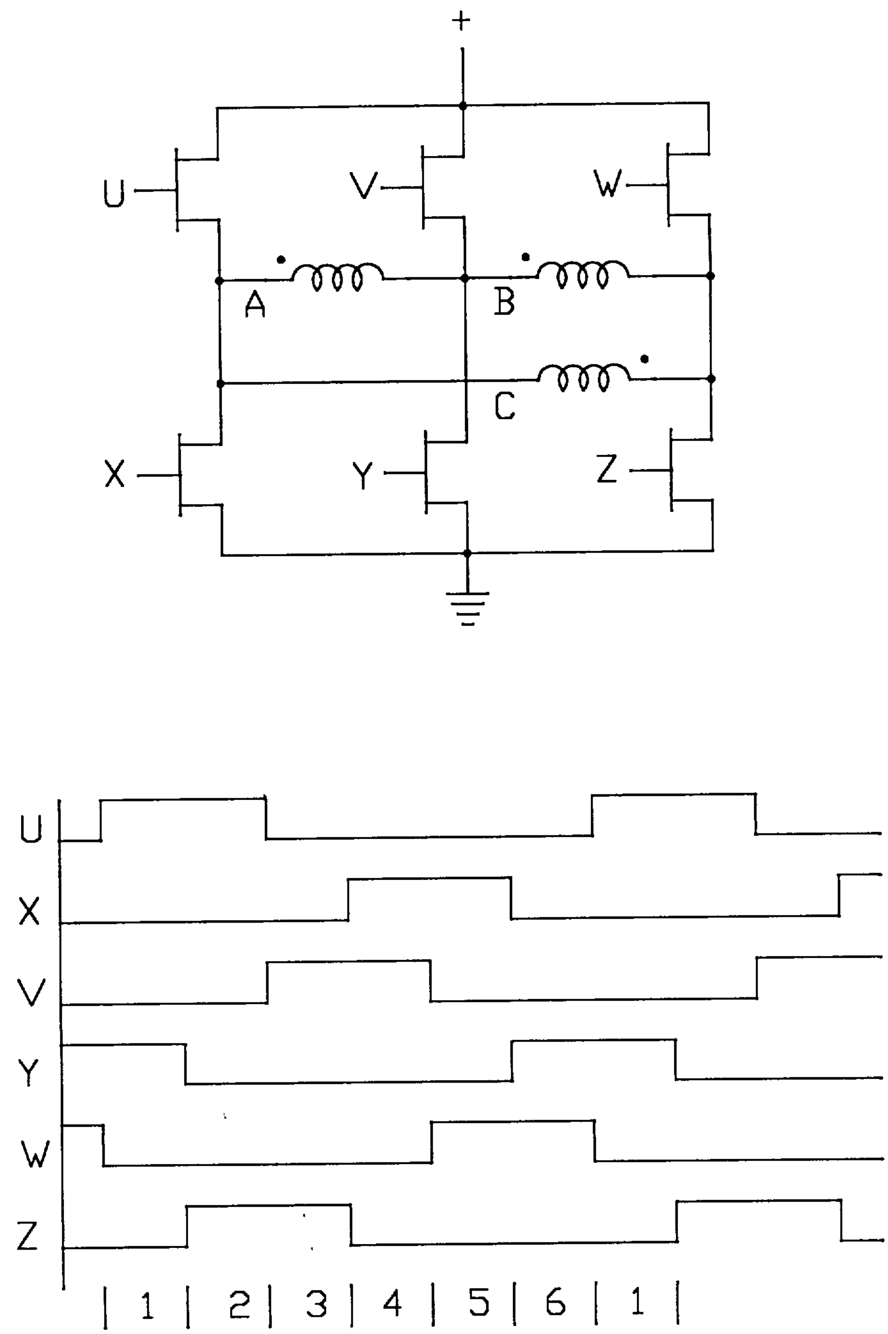


FIG. 11

Three Phase Delta Drive

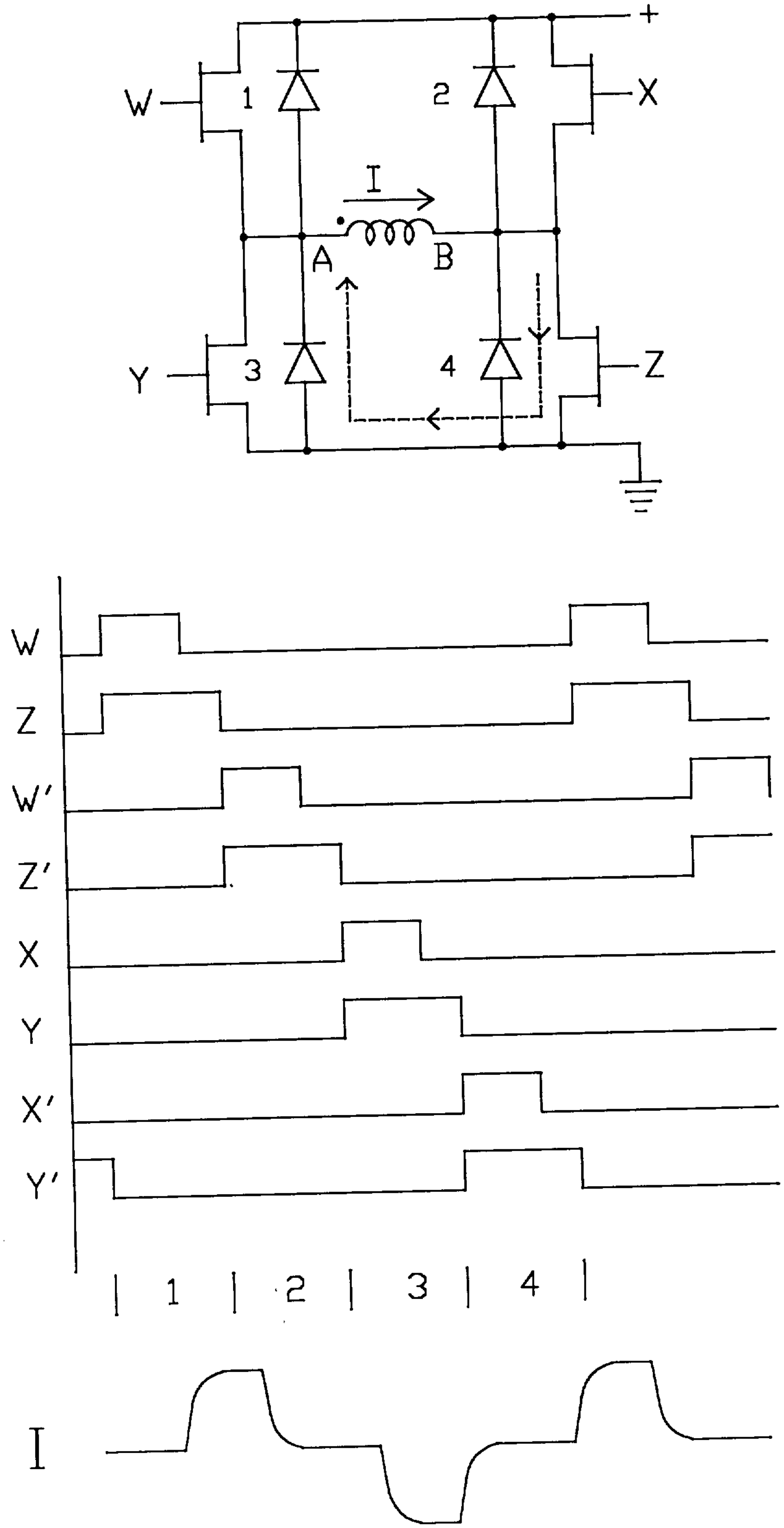


FIG. 12
Bipolar Drive with
Motor Inductance Discharge Path

Torque Profile of Two Phase Stepper

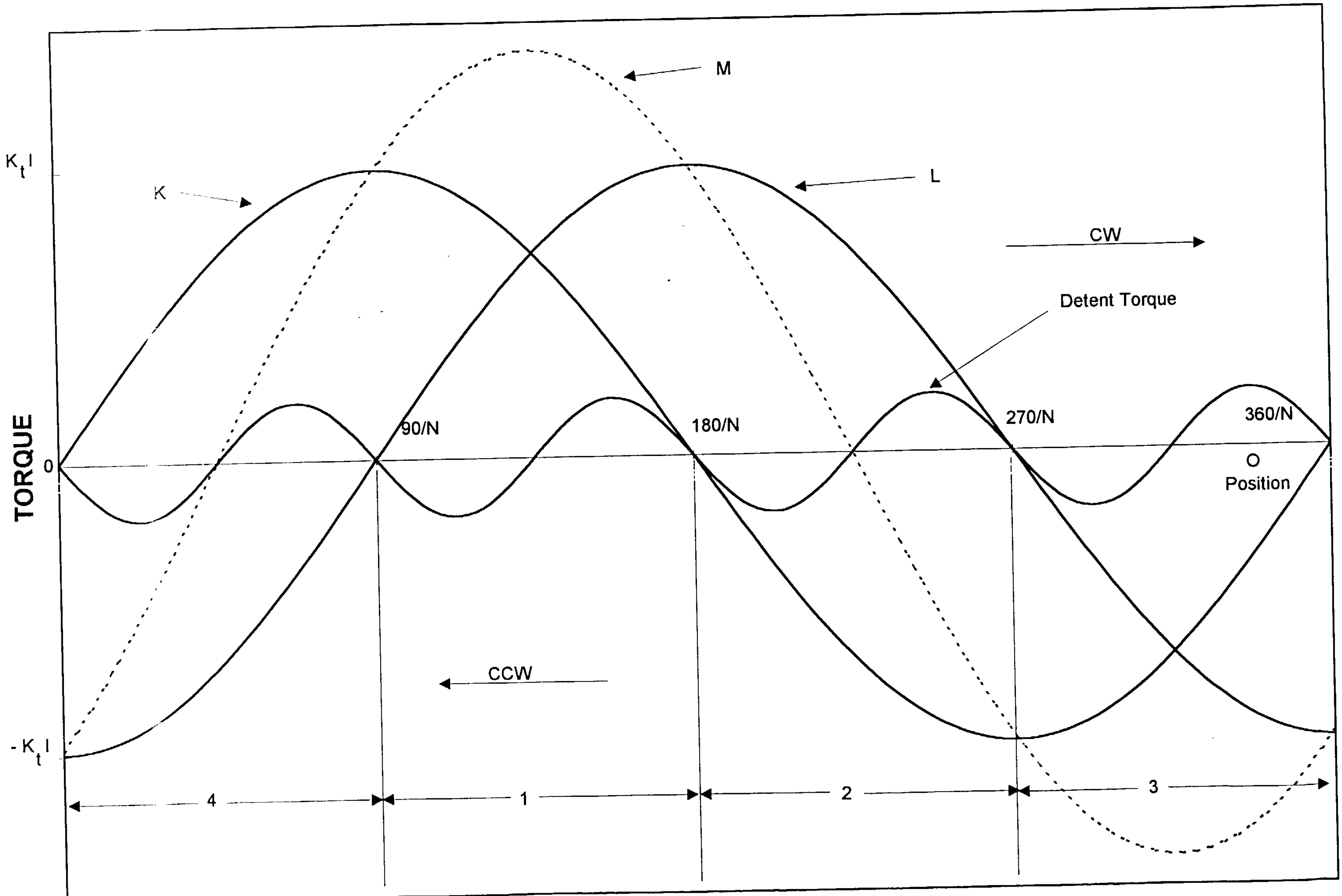


FIG. 13

Torque Profile of Three Phase Stepper

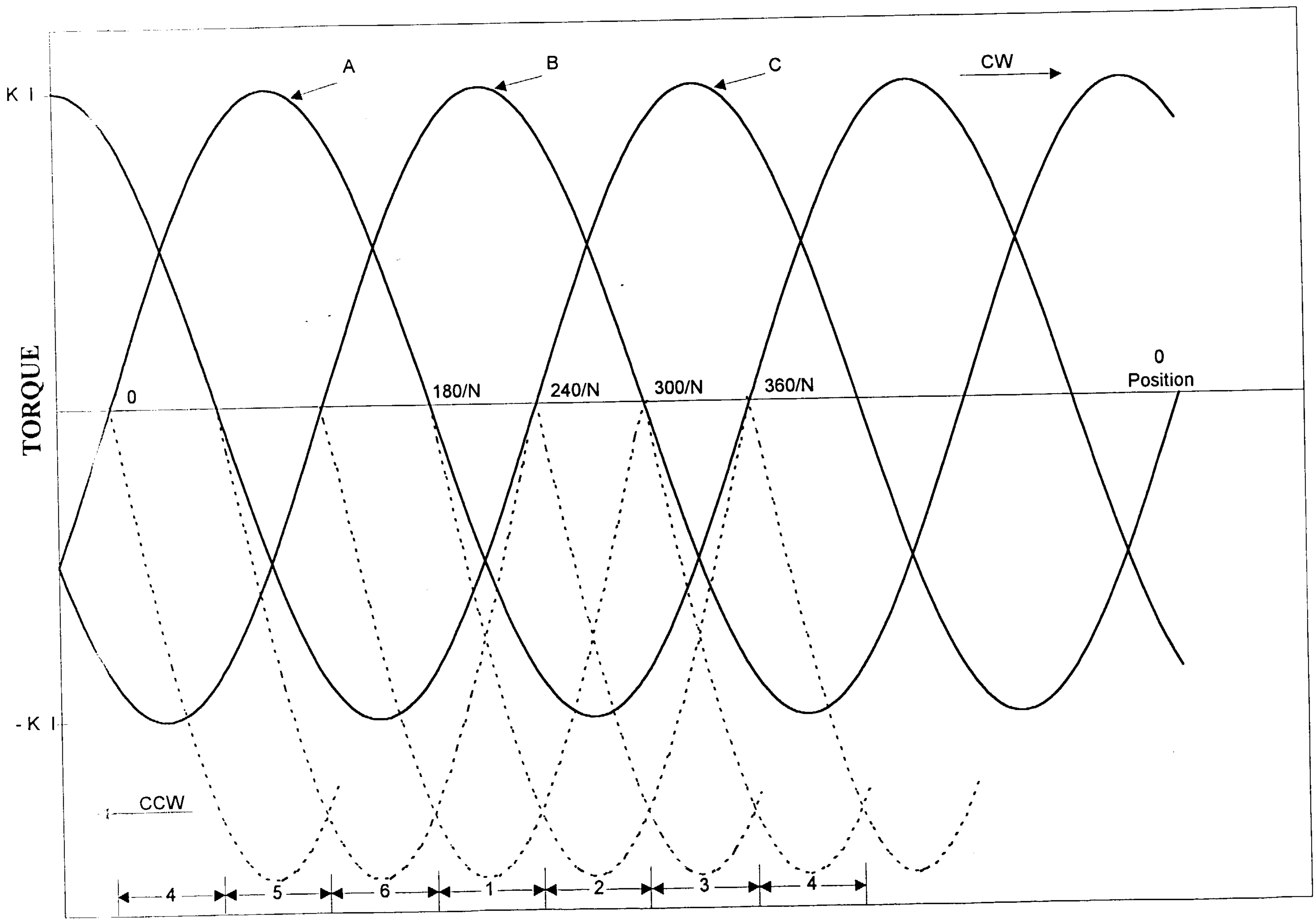


FIG. 14

Combined Torque Profiles of Single Phase Driven Stepper

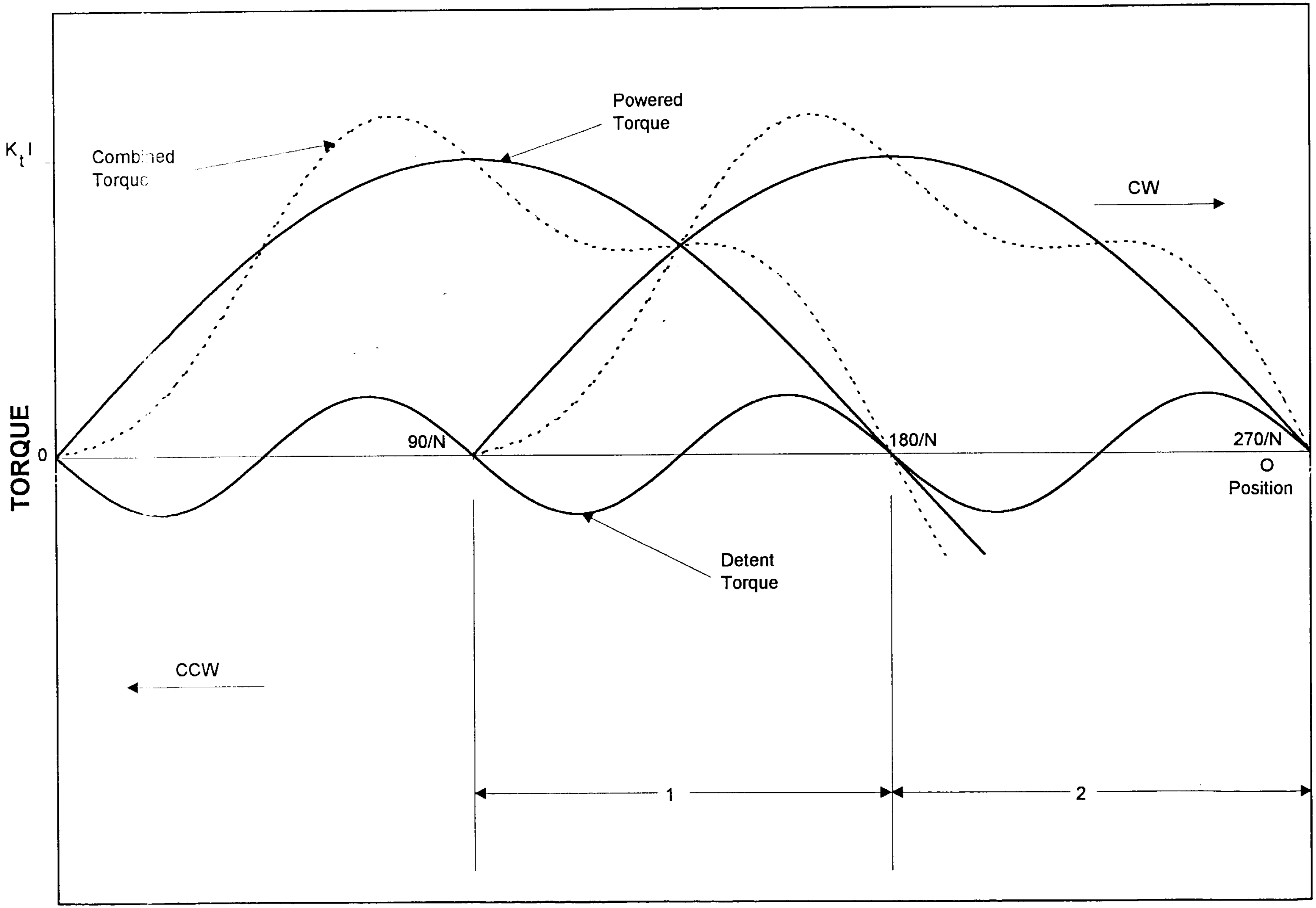


FIG. 15

Combined Torque Profiles of a Dual Phase Stepper

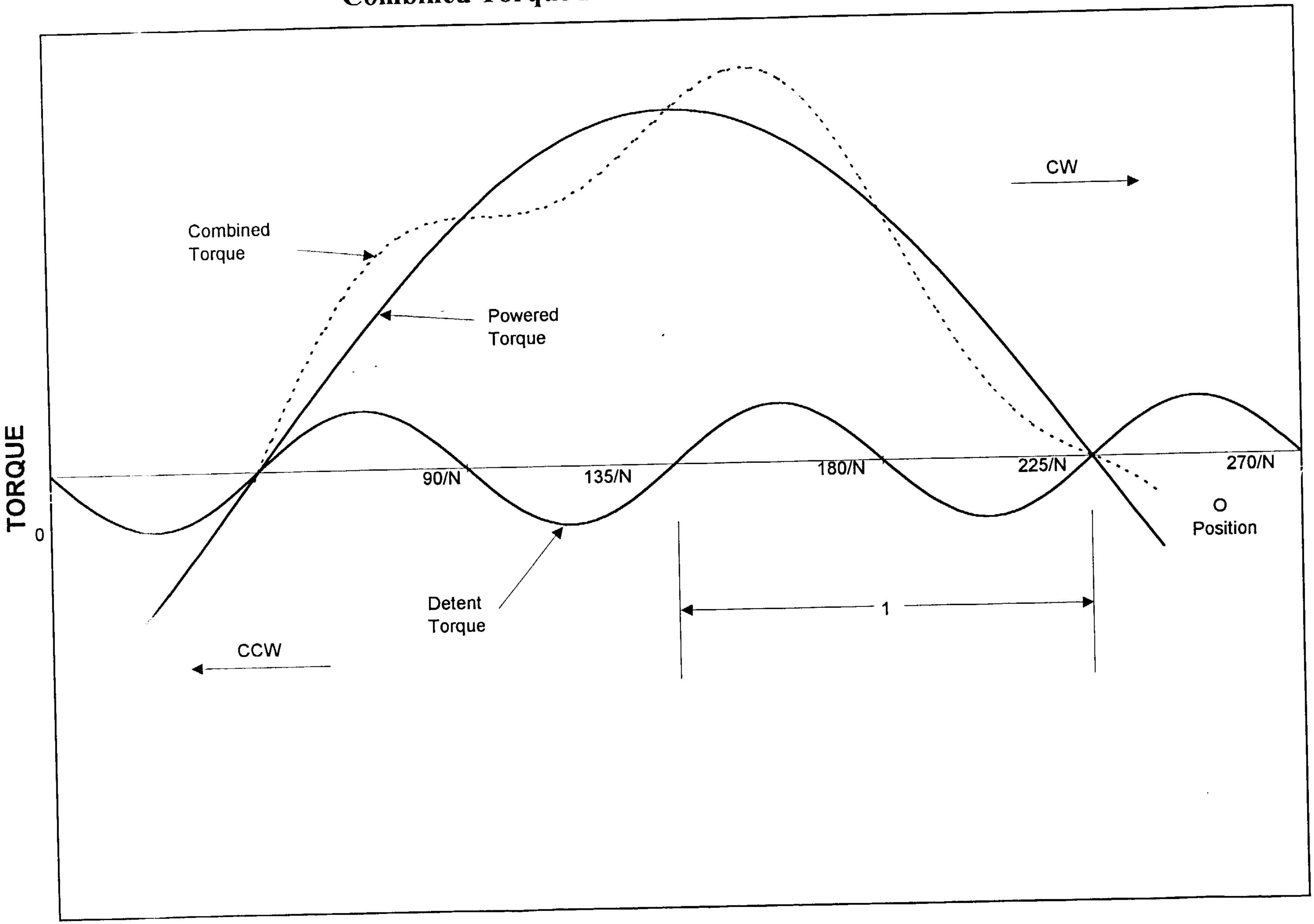


FIG. 16

Combined Torque Profiles of a Three Phase Stepper

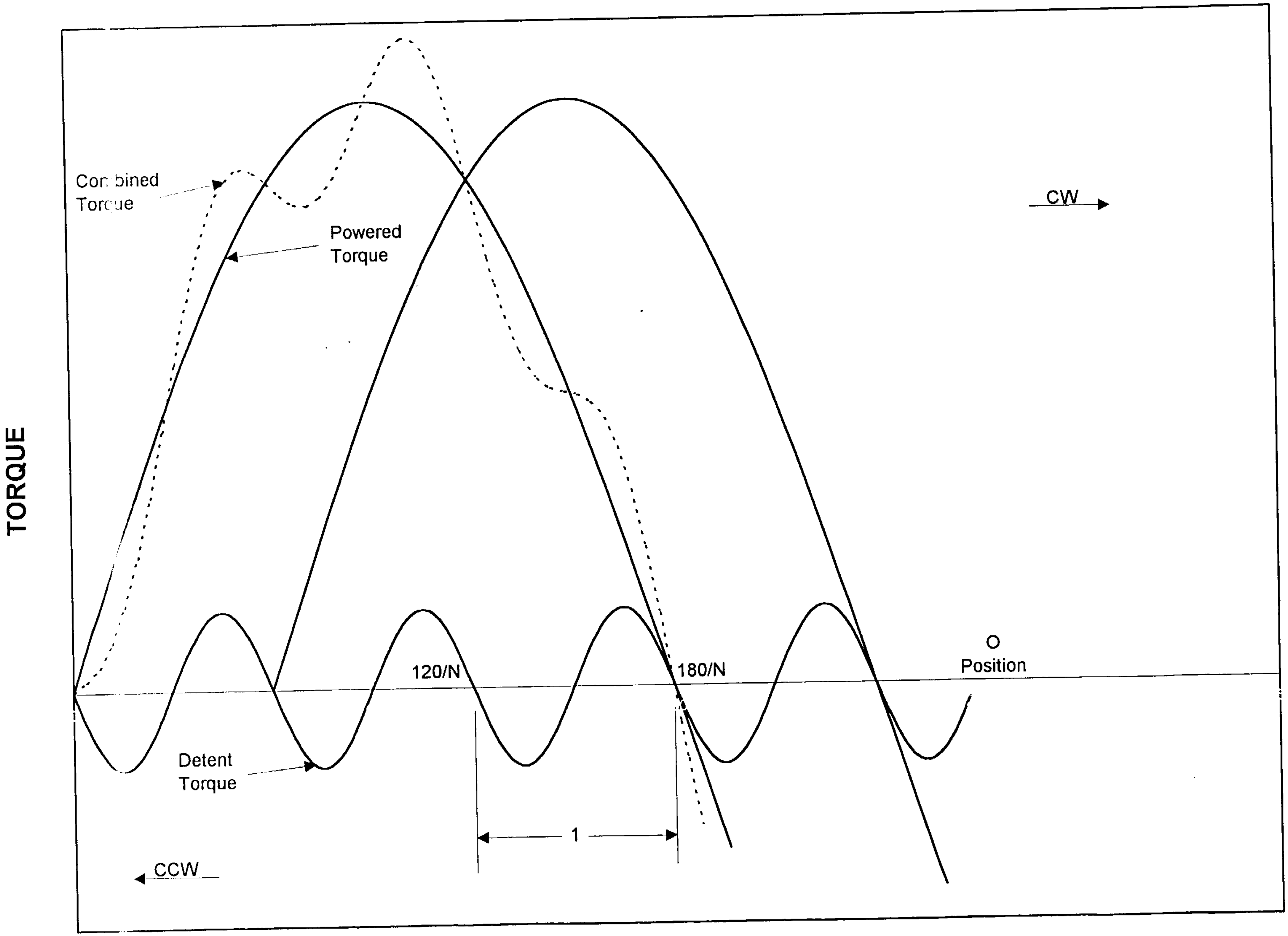
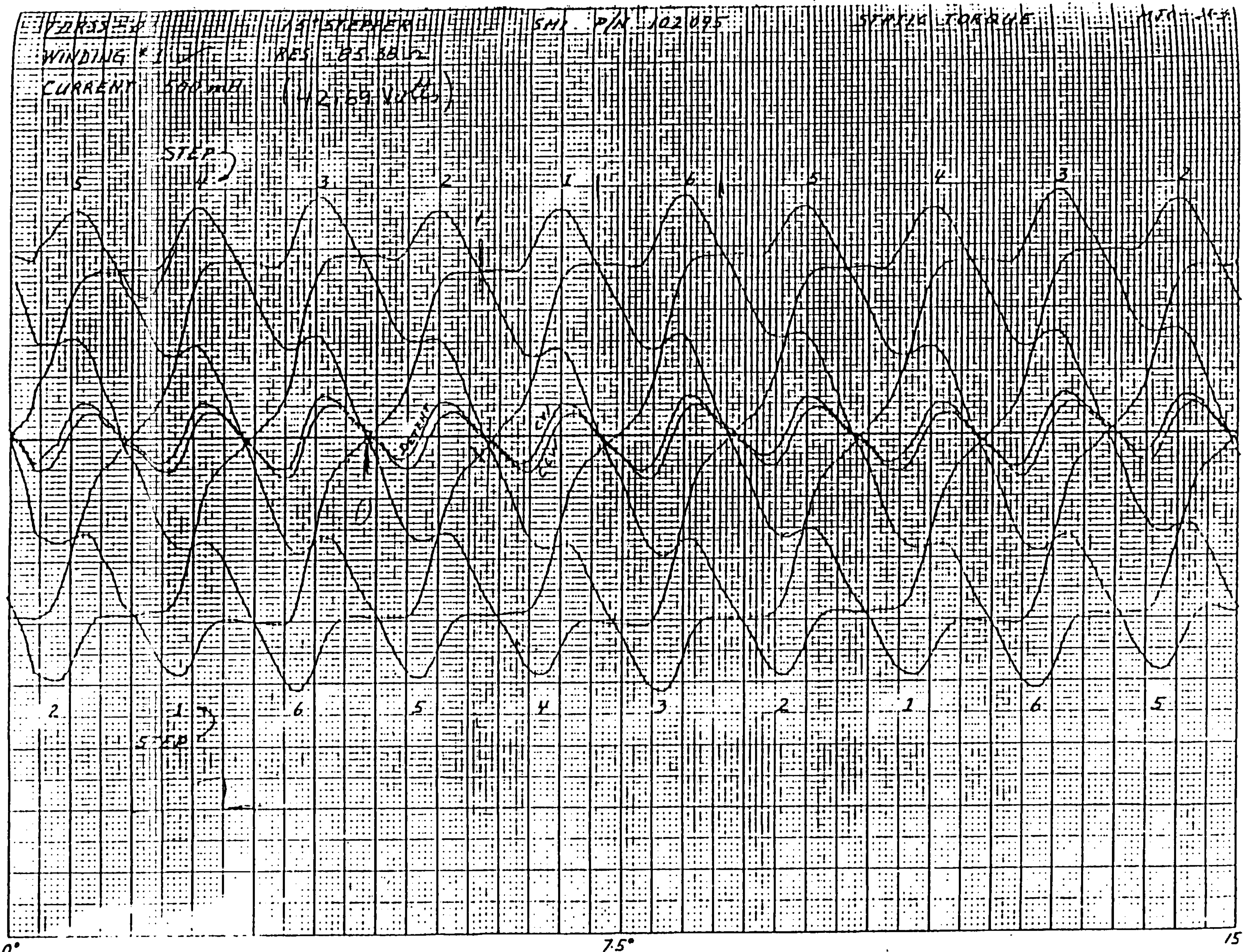


FIG. 17



MEASURED TORQUE PROFILES OF A THREE PHASE STEPPER
FIGURE 18

Torque Profile with Friction

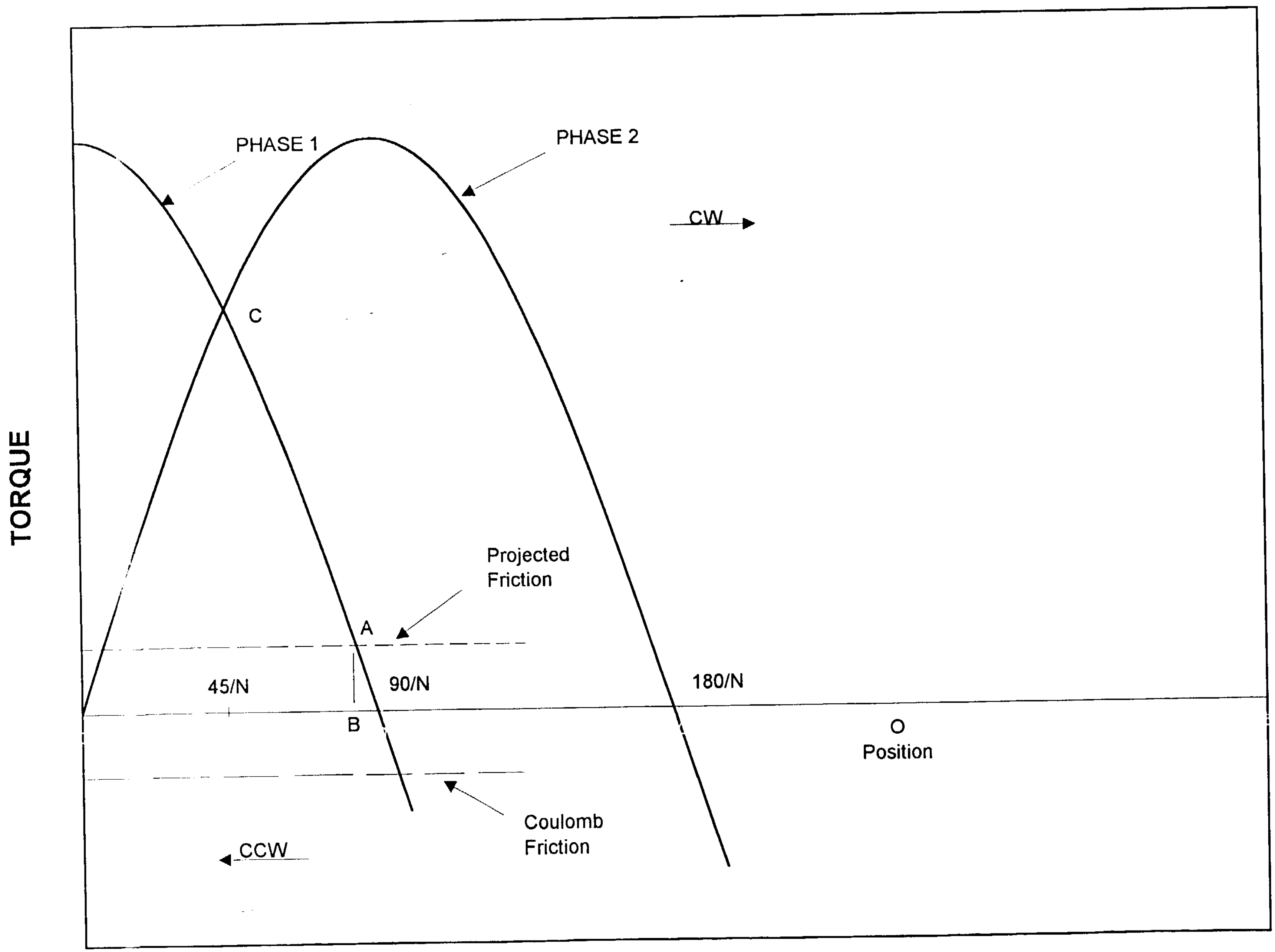


FIG. 19

Motor Torque Measurement Configuration

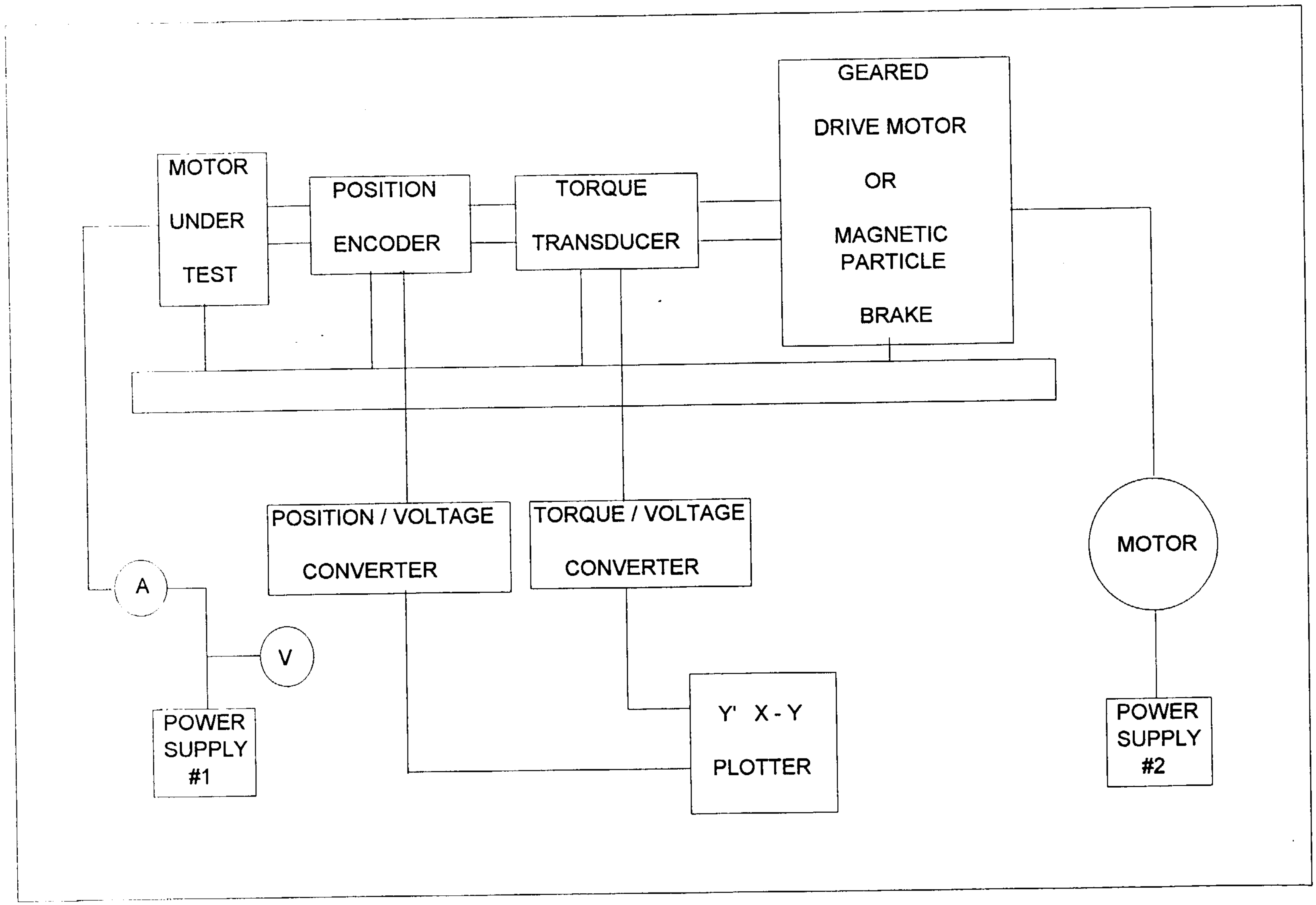


FIG. 20

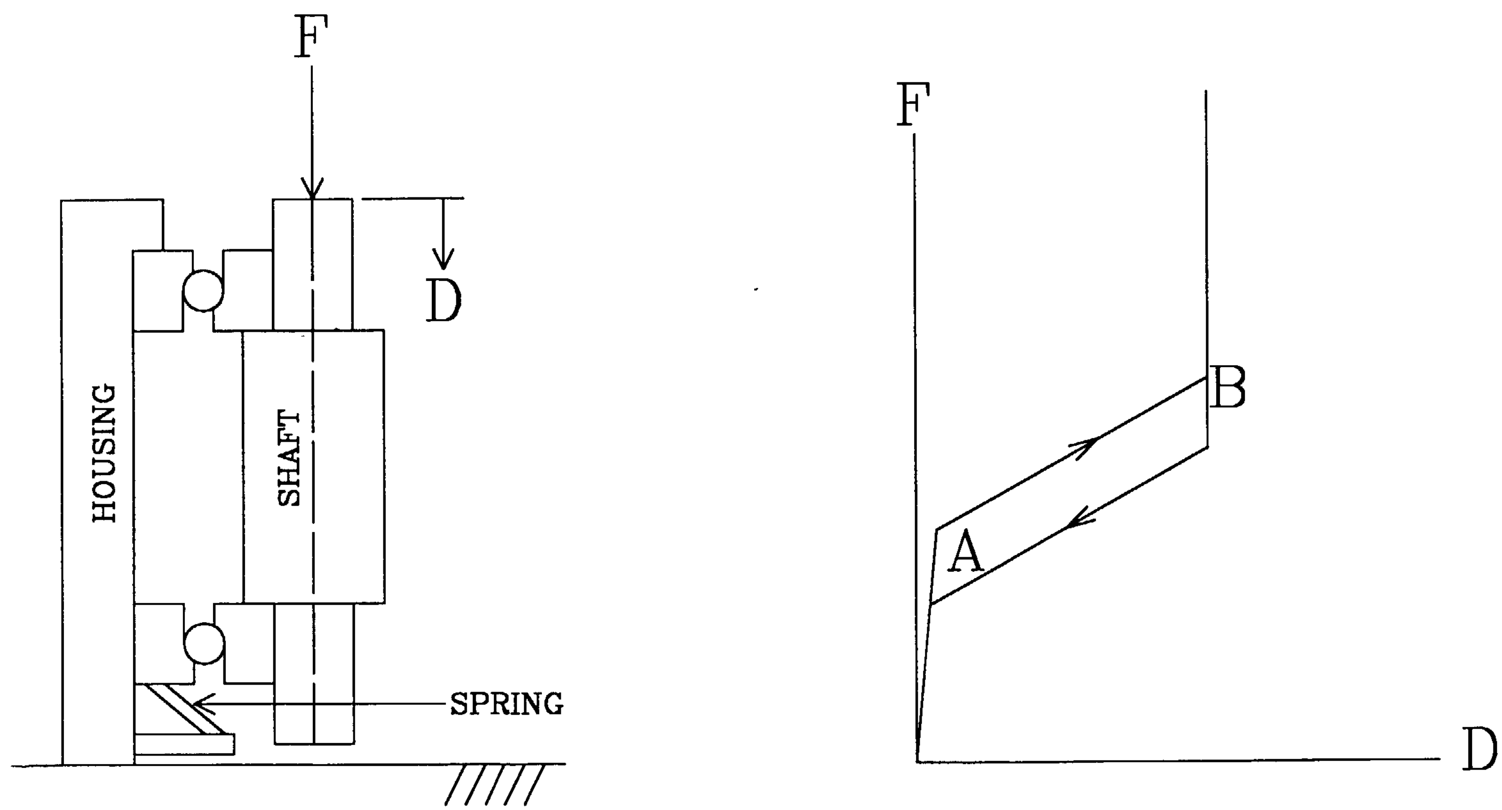


FIG. 21
PreLoad Measurement Configuration

APPENDIX

TORQUE RATIO

SECIFICATION

Torque Ratio

The torque ratio (TR) is a measure of the degree to which the torque available to accomplish a mechanical function exceeds the torque required. The torque ratio is simply the ratio of the driving or available torque to the required or resistive torque. Numerically, the torque margin is the torque ratio minus one. The torque ratio requirement defined below applies to all mechanical functions, those driven by motors as well as springs, at beginning of life (BOL) only; end of life (EOL) mechanism performance is determined by life testing as discussed in paragraph 3.4.4.3. For linear devices, the term "force" shall replace "torque" throughout this section.

For final design verification, the torque ratio shall be verified by testing the qualification unit both before and after exposure to qualification level environmental testing. The torque ratio shall also be verified by testing all flight units both before and after exposure to acceptance level environmental testing. All torque ratio testing shall be performed at the highest possible level of assembly, in all operational positions of the mechanism, under worst-case BOL environmental conditions which represent the worst-case combination of maximum and/or minimum predicted (not qualification) temperatures, gradients, voltage, vacuum, etc.

The required tests are:

a. The minimum available torque of the prime mover, T_{avail}, shall be verified by testing of individual motors, deployment springs, etc., in all positions. The measurement of available torque shall not include the mechanical advantage of harmonic drives or gear systems. Kick-off springs which do not operate over the entire range of the mechanical function shall be neglected. The minimum available torque shall be never be less than 1 in-oz.

b. The maximum resistive torque of the driven system, T_{res}, shall be verified by testing of the fully-assembled, driven portion of the mechanism in all positions. For systems that include (velocity dependent) dampers, appropriate measures shall be employed to characterize (as nearly as possible) only the frictional resistive torque.

The torque ratio is then given by:

$$TR = \frac{T_{avail}}{T_{res}}$$

The minimum required test-verified torque ratios for various types of mechanism systems prior to environmental testing are:

	TR_{min}
Systems which are dominated by resistive torques due to inertia, such as momentum and reaction wheels	1.25
Systems which are dominated by resistive torques due to a combination of both inertia and friction, such as large pointing platforms and heavy deployable systems	2.25
Systems which are dominated by resistive torques due to friction, such as deployment mechanisms, solar array drives, cable wraps, and despun platforms	3.0

After exposure to environmental testing, the reduction (if any) in test-verified torque ratio shall be no greater than 10%, after appropriate consideration has been given to the error inherent in the test methods used to measure the torque ratio.

The required torque ratios should be higher than given above for designs involving an unusually large degree of uncertainty in the characterization of resistive torques, when torque ratio testing is not performed in the required environmental conditions or is not repeatable, or when torque ratio testing is performed at the component level.

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13. ABSTRACT *(Maximum 200 words)*

The purpose of this document is to describe the more commonly used permanent magnet stepper motors for spaceflight. It will discuss the mechanical and electrical aspects of the devices, their torque behavior, those parameters which need to be controlled and measured and test methods to be employed. It will also discuss torque margins, compare these to the existing margin requirements and determine the applicability of these requirements. Finally, it will attempt to generate a set of requirements which will be used in any stepper motor procurement and will fully characterize the stepper motor behavior in a consistent and repeatable fashion.

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